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Study of natural ventilation in wind tunnels and influence of the position of ventilation modules and types of grids on a modular façade system

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Abstract

Natural ventilation requires no energy consumption, which can constitute 25% of a mechanically ventilated building, and both shape and position of inlets and outlets ventilation openings must be properly designed for better natural ventilation performance. Wind tunnel tests are a reliable tool for the determination of the effect of natural ventilation on buildings. This paper reports on results of wind tunnel tests conducted for the evaluation of the influence of the positioning and type of grid of ventilation modules on a façade system. Three ventilation modules were positioned below the window-sill (ventilated window-sill) and three were positioned above and below the façade. Ventilation modules with grid elements positioned vertically and horizontally were tested. Wind speed measurements that considered single-sided and cross ventilation were taken inside and outside the model for the different façade configurations for the evaluation of the best performance in relation to natural ventilation. The façade system proposed is movable and interchangeable, so that the same basic model can be used for the testing of possibilities for ventilation. The results show the use of six ventilation modules positioned below the window-sill and that form a "ventilated window-sill" with a horizontal grid is the best solution regarding natural ventilation. Such a configuration has proved the grid elements of ventilation modules exert a higher influence on the results than the positioning of modules on the façade. Therefore, better conditions of natural ventilation were obtained with a thin and horizontal positioning of the elements.

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Keywords: Façade; Natural Ventilation; Wind Tunnel Tests.

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1. Introduction

A façade is the part of a building that forms the primary thermal barrier with its environment. It represents the most important factor for the determination of the level of thermal comfort, daylighting and ventilation and amount of energy required for the heating and cooling of the environment.

The positions of window openings are important parameters for the analysis of the effectiveness of wind-driven cross-ventilation in buildings. Therefore, natural ventilation can save the energy consumed by the heating, mechanical ventilation, and air-conditioning systems in a building if it provides acceptable indoor air quality and thermal comfort levels [1]. Appart from the evaluation of the positioning of the ventilation openings, if it is not completely unobstructed, the elements present in the facade and their behavior in contact with the wind must also be evaluated, as in the examples provided in this study, for analyses of the type of grid elements under ventilation conditions.

Ventilation significantly impacts on several important human responses. Low ventilation rates may result in increased concentrations of indoor generated pollutants, which may be associated with sick building syndrome symptoms, comfort (perceived air quality), health effects (inflammation, infections, asthma, allergy), and productivity. Therefore, ventilation requirements draw major attention in building regulations. Ventilation standards tend to cluster around common values for recommended ventilation rates and rates higher than 0.3 h-1 have been adopted in some countries. In practice, ventilation is often poor, which results in high concentrations of pollutants, hence, risks to health [2]. Studies on ventilation are necessary, because good ventilation implies in a better productivity and health of users of buildings and yet promotes energy efficiency.

Regarding wind velocities, Olgyay [3] and Evans [4] observed air velocities up to 0.25 m/s are imperceptible and cause no cooling sensation to users. According to the authors, speed values between 0.25 and 0.50m/s are pleasant and provide a feeling of fresh. Evans and Schiller [5] highlighted values up to 0.5m/s cause no cooling effect, however, above this value, a perceptible movement of air is created for a cooling effect. The maximum speed of indoor air is defined by factors, such as physiological comfort, type of building and use. The limit is 0.8m/s for offices and commercial buildings, whereas for industrial environments, 1.5m/s is acceptable for assisting in the removal of toxic substances, heat or other harmful conditions. For residential buildings, the maximum speed recommended is 1 m/s [6].

Ben-David and Waring [7] simulated the impacts of natural versus mechanical ventilation in offices on indoor concentrations of key pollutants and energy usage. A typical office building was modeled in EnergyPlus in fourteen U.S. cities for the assessment of the energy use and airflows delivered by an ideal variable air volume (VAV) system in a range of climates. Two mechanical ventilation strategies, namely minimum and minimum and economizer control and two analogous natural ventilation strategies that used a fan-driven recirculation hybrid system to maintain setpoints, if necessary, were modeled. The study demonstrated the use of natural ventilation, rather than mechanical ventilation, can change both energy use and indoor air concentrations. The cooling energy was reduced under all ventilation strategies in comparison to the mechanical minimum strategy. The use of natural ventilation promoted the largest reduction, by saving energy, and provided a wider temperature setpoint band. The heating energy was often reduced by natural ventilation strategies, due to the wider setpoint band.

In studies on ventilation, wind tunnel tests are a reliable tool for the determination of the effects of wind loads on civil engineering structures and influence of natural ventilation on buildings, which is the specific purpose of this research. In a wind tunnel, speed and wind direction are controlled and small models simulate the natural ventilation of buildings. Natural ventilation, which renews the air in a closed environment with no use of mechanical elements, can lead to energy savings, as it avoids the use of air conditioning systems and improves the air quality.

Chu et al. [8] conducted wind tunnel experiments to investigate the wind-driven ventilation for buildings with two openings on a single wall. The exchange rates were measured by the tracer gas decay method under different external wind speeds, directions and opening sizes. The results show the time-averaged pressure difference across the openings is much larger than the fluctuating pressure when the wind direction is $\theta = 22.5^o - 45^o$ and the ventilation rate can be predicted by the orifice equation. When the wind directions are $\theta = 0^\circ$and $67.5^o - 180^o$, the pressure difference across the openings is insignificant and the fluctuating pressure entrains air across the openings. The exchange rate is proportional to the root-mean-square of the pressure fluctuation. Furthermore, the dimensionless exchange rate of the shear-induced ventilation (wind is parallel to the openings) is independent of the wind speed, opening area and location.

Ji et. al [9] investigated the influence of fluctuating wind direction on cross-ventilation through wind tunnel experiments for improving the evaluation accuracy of natural ventilation. A periodically fluctuating wind direction was designed and reproduced in the experiments. Rapid Response FIDs (Flame Ionization Detector) monitored the concentration of the tracer gas and an index named diluting flow rate (DFR) was introduced for the evaluation of the ventilation performance. The results show the DFRs of fluctuating cases are approximately 65 and100% of the maximum airflow rate and DFR is influenced by the wind speed, opening size and wind direction fluctuation.

Silva et al [10] reported results of airflow measurements taken inside a naturally ventilated double skin facade by a tracer gas technique. Wind tunnel tests were also performed at LNEC (*Laboratório Nacional de Engenharia Civil*) in a 9.0m long open circuit wind tunnel of 3.1 2.0 m^2 cross section. The airflow was provided by 1-6 fans of 11 kW that enabled a fine tuning of air velocity through a frequency regulator which reached up to 18 m/s. The tests were carried out under uniform upstream flow at approximately 10.5 m/s. A 1:100 scale model of the test cell and surrounding buildings was assembled for the assessment of wind pressure coefficients on the outer louvers. The estimation of natural ventilation airflow rates is a key issue for the design of a double skin façade, however, it involves a nontrivial task, given the dynamic nature of the phenomena and complexity of the flow measurement. The relative contribution of both thermal and wind driving forces to the natural induced flow in the cavity was also investigated. The pressure difference was dominant over the stack effect in most tests.

Wind tunnel tests performed with reduced scale models increase the reliability and effectiveness of a construction, reduce costs and enable the evaluation of both influence of other buildings, surroundings and ground on the ventilation of buildings and quality of indoor air in relation to the dispersion of pollutants and contaminants. Moreover, they enable a more efficient study of the ventilation of indoor environment and optimization of the distribution of windows for better environmental comfort, as in the present research. Such tests can be used, for example, in study cases, as direct cross-ventilation and downwind or windward ventilation, for the positioning of the opening to the wind (normal, parallel or inclined to the flow direction of ventilation) and for analyses of the elements present in the facade and their behavior in contact with the wind, as in this study.

This manuscript reports results of wind tunnel measurements based on the importance of natural ventilation for buildings. A study of the influence of ventilation modules positioning and type of grid on a modular façade system was conducted. Both positioning of ventilation modules and grid type were modified in the façade configuration for the evaluation of the results in the average air velocity at specific points. The research is part of a major study of a modular facade system for Portugal [11] [12] [13] and such ventilation solutions can be used in the south of the country during the summer season.

2. Materials and Methods

The development of the research included the characterization and preparation of the wind tunnel, design of the model and acrylic façades, and assembly and installation of the sensors.

2.1. Wind Tunnel

The wind tunnel used (Fig.1) is the one of the Laboratory of Environmental Comfort and Applied Physics, Faculty of Civil Engineering, Architecture and Urbanism, at University of Campinas – UNICAMP, which operates with an axial fan sucking air. Figure 2 shows the tunnel inside the laboratory.

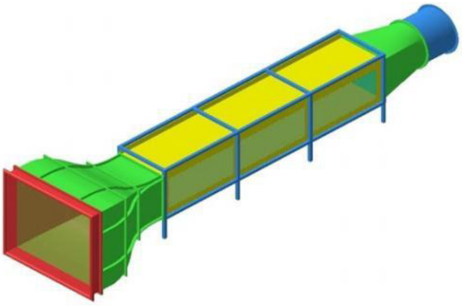

Fig. 1. Overview of the Wind Tunnel (Matsumoto, 2008).

Fig.2. Wind Tunnel - UNICAMP.

The cross-section of the chamber test is 0.9m wide by 0.8m high and its area comprises 0.72m². The turbulence inside it is generated by a roughened surface and zero pressure gradient (due to the creation of a turbulent boundary layer). Other details include total length of 9.03m, 4.80 m length of the test section, 1.20 m diameter of the fan blades, with a total of 16 blades, and output diameter of 1.25m.

The characteristics of the flow in the wind tunnel of an atmospheric boundary layer should be similar to those found in the atmospheric environment near the surface, so that the vertical velocity gradient in the tunnel test section would range from zero at the surface to the value of the free flow speed, with no interference of surface roughness. The layer changed by the speed is called boundary layer. Turbulators, which are obstacles located along the entrance tunnel test section [14] (Fig. 3) produce the velocity gradient and turbulence in the flow.

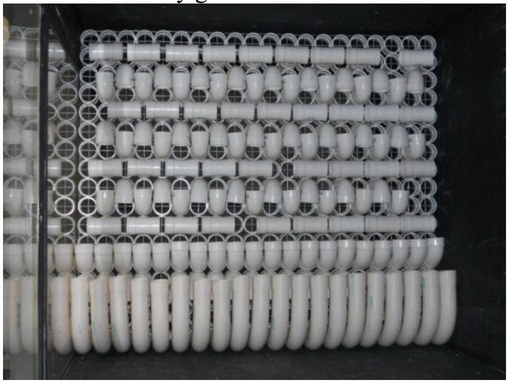

Fig. 3. Posterior view of the panel composed of PVC tubes that simulate turbulence near the wind tunnel air inlet.

2.2. Model

The definition of the model characteristics is fundamental for the development of wind tunnel tests. The phenomenon observed in both the model and the prototype (the real building) must be equivalent if the rules of physics and conditions contour are similar. As the dimensions of the test section of the wind tunnel are 0.9m width by 0.8m height and the total cross-sectional area is 0.72m², the obstruction test section rate should range between 5% and 7%. The model can block at most 7% of the cross-sectional area perpendicular to the wind incidence. Therefore, the façade of the model, which is normal to the wind incidence, can be at most 0.05m². No dimension restrictions are imposed on the horizontal direction along the wind tunnel.

The model was built on a 1:20 scale of 0.16m height, 0.28m width and 0.28m length and 0.045m² frontal area. The cross-sectional obstruction of the wind tunnel is 6.3%. Table 1 shows the dimensions of the model and the real dimensions.

Table 1: Dimensions of the Model.

Measures	Real Dimensions (m)	Models Dimensions (m)
Height	3.20	0.16
Width	5.65	0.28
Length	5.65	0.28
Scale		1:20
Section area (m^2)		0.72
Frontal area of the model (m^2)		0.045
Cross-sectional obstruction of the wind tunnel (%)		6.3

The model was manufactured with wood paper of 1, 2 and 3 mm thicknesses and connected by PVA glue (Figs. 4 and 5).

Fig. 4. Model.

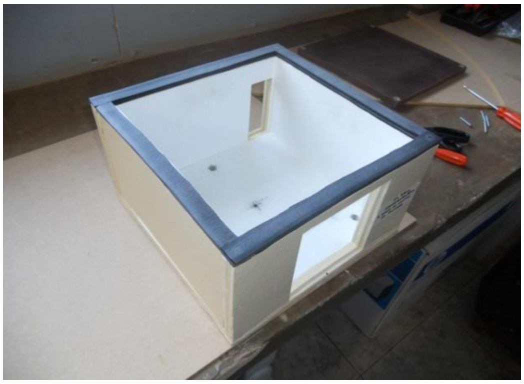

Fig. 5. Open.Model

The acrylic parts (variations of façades of 2.5m x 2.5m and 2mm thickness) were cut at the Laboratory of Automation and Prototyping for Architecture and Construction (LAPAC), Faculty of Civil Engineering, Architecture and Urbanism (FEC) of UNICAMP (Fig. 6).

The facades proposed are mobile and interchangeable, so that the same base model can test possibilities of ventilation. Four variations of the facade positions, whose characteristics are described below, were built and each ventilation module has 0.50 x 0.50 m dimensions.

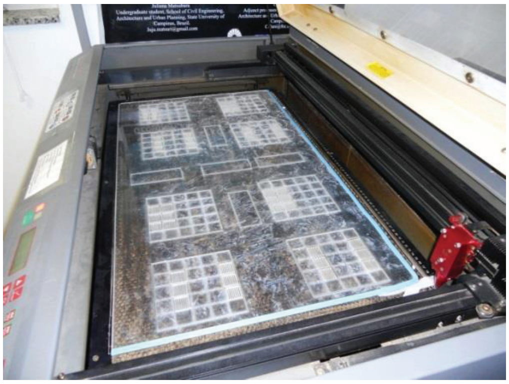

Fig. 6. Confection of the acrylic facades Prototypes by a laser cutter.

Six ventilation modules positioned below the window-sill (ventilated window-sill) (Case 01A), three above the façade and three below it (Case 01B with grid elements positioned vertically were tested. Six ventilation modules positioned below the window-sill (ventilated window-sill) (Case 02A), three above the façade and three below it (Case 02B) (Fig. 7) were tested with grid elements positioned horizontally. Each module was tested twice, i.e., with the door of the model open and closed.

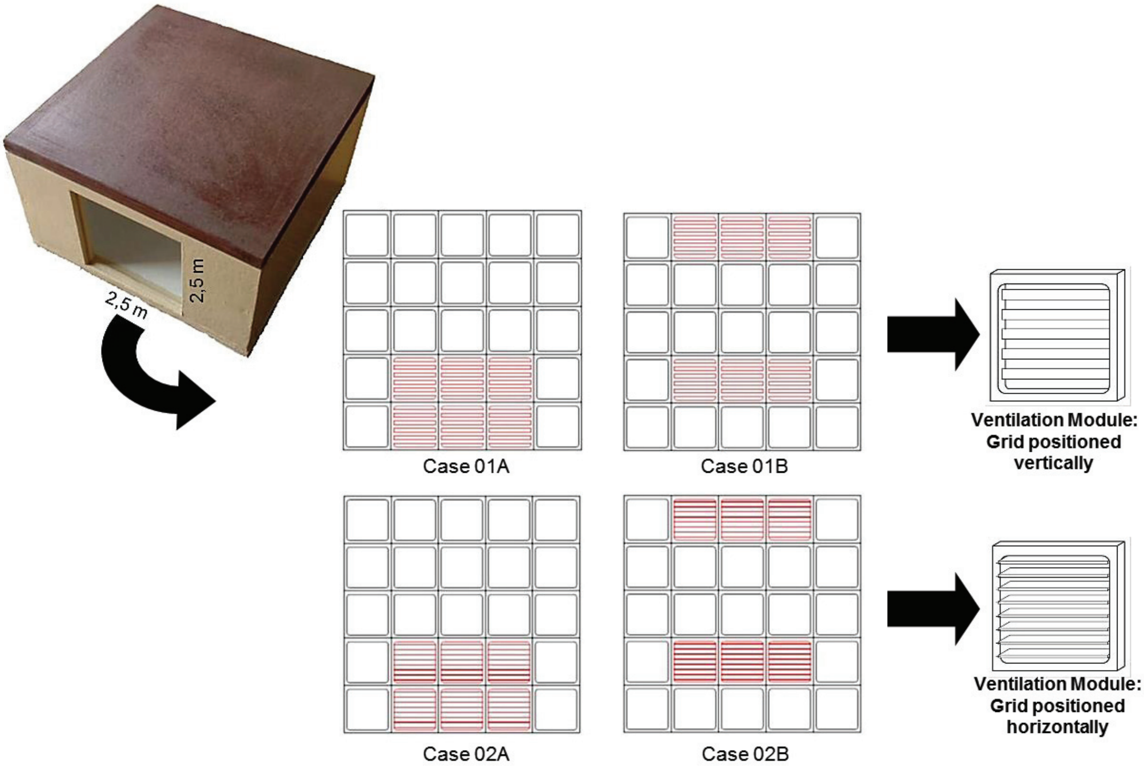

Fig. 7. Variations of the façades analyzed in the wind tunnel.

The tests evaluated the internal and external speeds for each configuration and showed the influence of the variations on the obtaining of more efficient natural ventilation. The most important values of the velocity measurements in the wind tunnel are the indoor values in relation to the speed of incidence on the façade.

Three-sensor hot wire anemometer thumbnails were installed inside the wind tunnel, through holes at the bottom, for the measurements of the internal speeds. The indoor sensors (P2, P3 and P4) were positioned 0.80m from the floor on a 1/20 scale, which corresponds to a person seated, and two external sensors were installed on the outlet air opening (door) (P5 and P6) for the obtaining of the wind speed when the air left the model.

Sensor (P1) was installed in the main façade for the measurement of the speed of the external wind before it had reached the physical model. Figures 8a-b show the positioning of the sensors inside the model (P1).

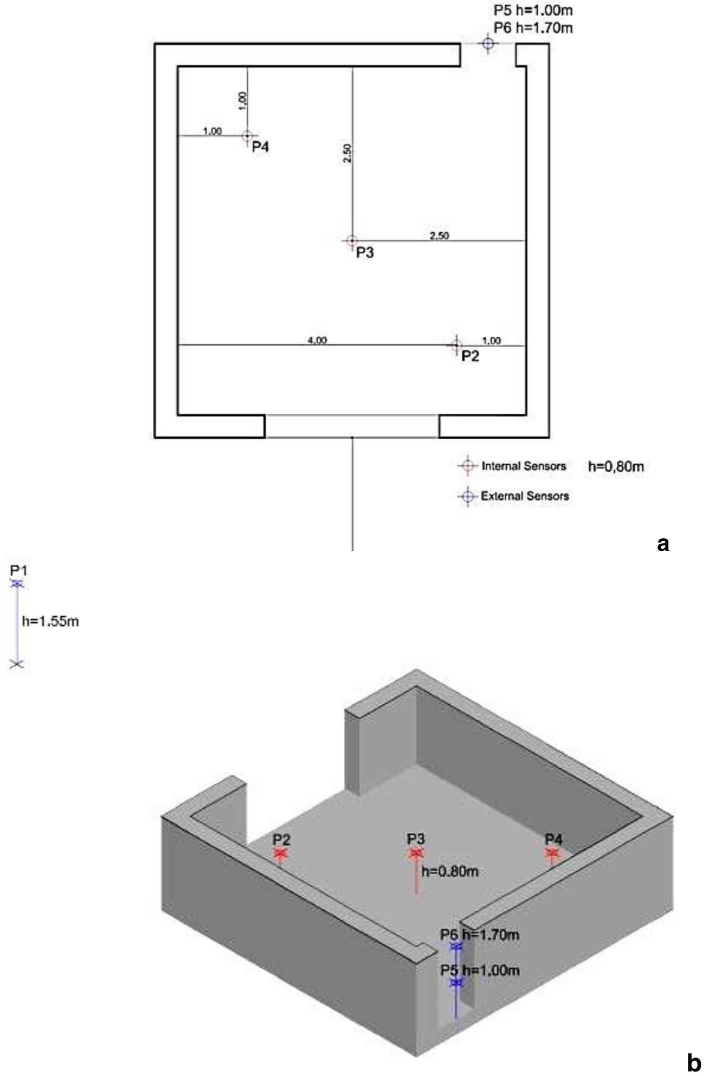

Fig. 8. Positioning of the sensors inside the model. Floor plan (a) and perspective (b).

Figures 9 and 10 show the model positioned inside the wind tunnel with the front sensor (P1) and the metallic supports and external sensors (P5 and P6) positioned at the air outlet of the model, respectively.

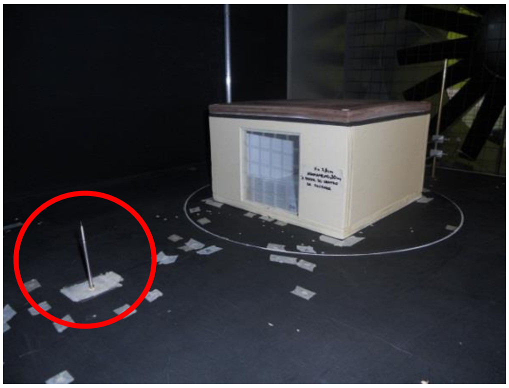

Fig. 9. Model positioned inside the wind tunnel and external sensor in front of the facade (P1).

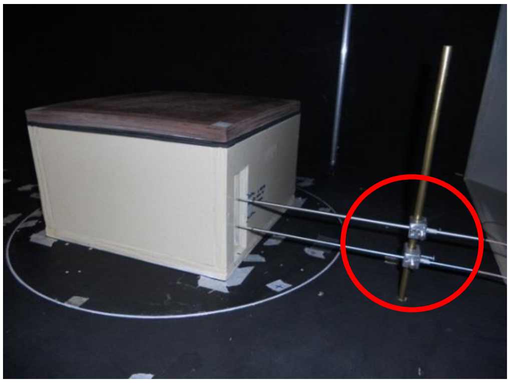

Fig. 10. Metallic supports and external sensors (P5 and P6) positioned at the air outlet of the model.

3. Results

Measurements were performed for comparisons of the speeds of variations in the façades and determination of the one of best performance regarding natural ventilation. Internal and external speeds were quantified by tests in the wind tunnel. The results of wind tunnel tests were achieved through the comparison of the internal speeds and the wind speed of incidence, close to the façade, so that the configuration with the best ventilation conditions could be determined.

- V1 = Wind speed at point P1, measured at a 1.55m height and 6m from the façade
- V2 = Wind speed at point P2, measured in the edge at a 0.80m height;
- V3 = Wind speed at midpoint P3, measured at a 0.80m height;
- V4 = Wind speed at point P4, measured in the edge at a 0.80m height;
- V5 = Wind speed at point P5, in the air outlet (door), measured at a 1.00m height;
- V6 = Wind speed at point P6, in the air outlet (door), measured at a 1.70m height.

3.1. Velocities of the Model with Cross Ventilation

Graphs show the air velocities inside and outside the model as a function of wind speed at point P1, measured at a 1.55m high and 6m from the façade (V1) for a better analysis of the results. In most cases, a linear trend was observed in the velocity variation in the points measured (cross ventilation results). The highest values were observed in the velocities measured for points outside the model and positioned at the outlet air opening (P5 and P6) (Figs. 11 to 14).

For cases 01, whose grid elements are positioned vertically (1A and 1B), the effective opening area in the façade was 0.61m² and the area of the door was 1,45m²; therefore, the area of the air outlet is larger than that of the input. The larger the size of the air outlet opening in comparison with the input, the higher the wind speed acquired, which may explain why higher speeds are observed in the points of air outlet (door) (P5 and P6).

The point positioned in the center (P3) resulted in higher values of speed, followed by P2 and P4. For Point P2, located inside the model on the edge next to the façade, the lowest values of speed were observed for Case 1B, whereas for point P5 (the lowest point of the air outlet), lower speeds were observed for Case 1B (Figs. 11 and 12).

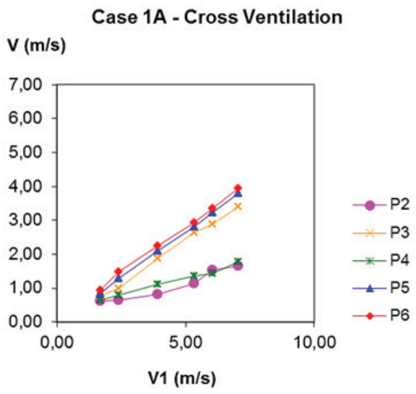

Fig. 11. Case 1A with cross ventilation: Speeds in internal points and speed on the facade (V1).

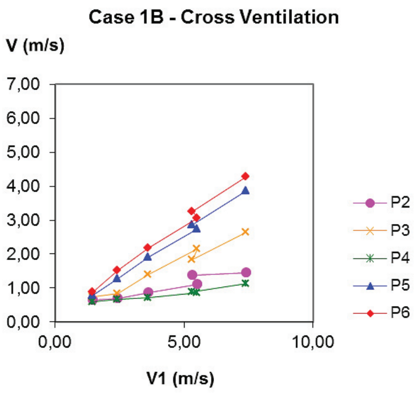

Fig. 12. Case 1B with cross ventilation: Speeds in internal points and speed on the facade (V1).

For cases 2A and 2B, whose elements of ventilation grid were positioned horizontally, the effective opening area in the façade was 0.82m² and the area of the door was 1,45m². Therefore, the area of the air outlet is larger than the area of the input, which explains why higher speeds are observed in the points of air outlet (door) (P5 and P6).

The point positioned in the center (P3) resulted in higher values of speed, followed by P2 and P4. For Point P2, located inside the model on the edge next to the façade, the highest values of speed were observed for Case 2A in comparison to Case 2B. For P5 (the lowest point of the air outlet), lower speeds were observed for Case 2B (Figs. 13 and 14).

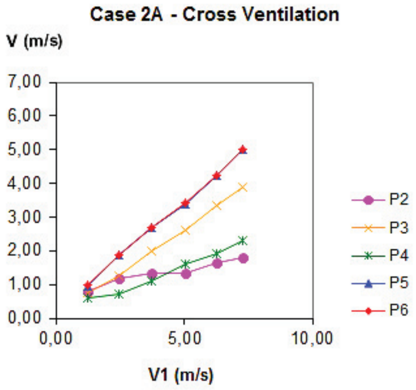

Fig. 13: Case 2A with cross ventilation: Speeds in internal points and speed on the façade (V1).

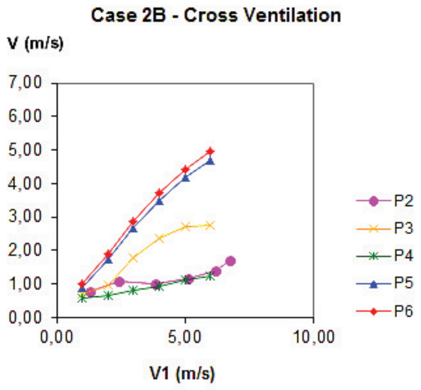

Fig. 14: Case 2B with cross ventilation: Speeds in internal points and speed on the façade (V1).

3.2. Velocities of the Model with no Cross Ventilation

Practically the same results were achieved with the model´s door closed, i.e., with no cross ventilation (Figs. 15 to 18). Although this study was conducted for a model that represents a unique environment of a building, poor natural ventilation may result in an increased concentration of indoor pollutants, bad thermal comfort conditions, health effects, and influence on the productivity of people that use the building.

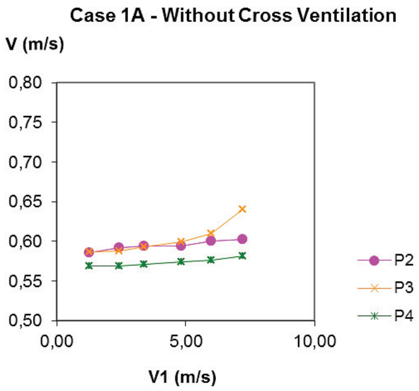

Fig. 15. Case 1A: Without cross ventilation: Speeds in internal points and speed on the facade (V1).

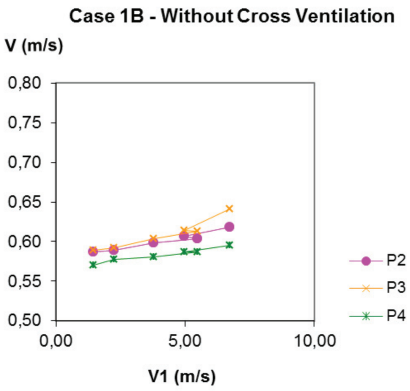

Fig. 16. Case 1B: Without cross ventilation: Speeds in internal points and speed on the facade (V1).

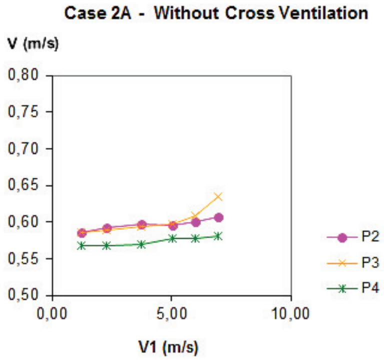

Fig. 17: Case 2A: Without cross ventilation: Speeds in internal points and speed on the façade (V1).

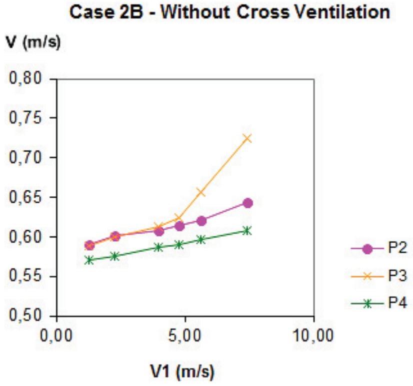

Fig. 18: Case 2B: Without cross ventilation: Speeds in internal points and speed on the façade (V1).

The speeds in internal points P2, P3 and P4 ranged from 0.58 to 0,74m/s. Higher speeds were observed for central point P3, followed by point P2 (located near the facade end) and the lowest velocities were detected for point P4, which was far from the inlet and outlet openings for ventilation.

3.3. Ratio Between the Speeds Measured

Table 2 shows the results of the ratio between the speeds measured in the interior points (V2, V3, V4) and in the points of air outlet (door) (V5, V6) and the speed measured by the front point (V1) for each case analyzed. In all cases, the major ratio was observed for the central point (V3/V1) and the wind exit points (V5/V1 and V6/V1).

Overall, except the central point of the model (P3), the increase in the speed in the front point (V1) caused a decrease in the ratio values, probably due to the model interference in the flow, which increases the turbulence and causes an energy loss. Therefore, the speed increase near the facade was not completely transformed into speed gain in the interior of the model.

Table 2: Ratio Between Speeds Measured.

Frequency (Hz)	**Case 01A: Ratio Between Speeds Measured** (with and without cross ventilation)									
	V2/V1		V3/V1		V4/V1		V5/V1		V6/V1	
	1A A	1A F	1A A	1A F	1A A	1A F	1A A	1A F	1A A	1A F
3	0,36	0,47	0,47	0,47	0,39	0,46	0,50	-	0,56	-
5	0,27	0,24	0,41	0,24	0,33	0,23	0,54	-	0,62	-
7	0,21	0,18	0,48	0,18	0,29	0,17	0,54	-	0,58	-
9	0,21	0,12	0,49	0,12	0,25	0,12	0,53	-	0,55	-
11	0,25	0,10	0,48	0,10	0,24	0,10	0,53	-	0,55	-
13	0,23	0,08	0,48	0,09	0,25	0,08	0,54	-	0,56	-

Frequency (Hz)	**Case 01B: Ratio Between Speeds Measured** (with and without cross ventilation)									
	V2/V1		V3/V1		V4/V1		V5/V1		V6/V1	
	1B A	1B F	1B A	1B F	1B A	1B F	1B A	1B F	1B A	1B F
3	0,43	0,41	0,50	0,41	0,40	0,40	0,53	-	0,61	-
5	0,28	0,26	0,35	0,26	0,28	0,26	0,52	-	0,62	-
7	0,24	0,16	0,39	0,16	0,20	0,15	0,53	-	0,60	-
9	0,20	0,11	0,39	0,11	0,15	0,11	0,50	-	0,56	-
11	0,26	0,12	0,34	0,12	0,17	0,12	0,54	-	0,61	-
13	0,20	0,09	0,36	0,10	0,15	0,09	0,52	-	0,58	-

Frequency (Hz)	**Case 02A: Ratio Between Speeds Measured** (with and without cross ventilation)									
	V2/V1		V3/V1		V4/V1		V5/V1		V6/V1	
	2A A	2A F	2A A	2A F	2A A	2A F	2A A	2A F	2A A	2A F
3	0,65	0,47	0,60	0,47	0,48	0,46	0,76	-	0,78	-
5	0,48	0,26	0,52	0,26	0,30	0,25	0,77	-	0,76	-
7	0,36	0,16	0,53	0,16	0,29	0,15	0,72	-	0,72	-
9	0,26	0,12	0,52	0,12	0,31	0,11	0,67	-	0,67	-
11	0,26	0,10	0,54	0,10	0,30	0,10	0,67	-	0,68	-
13	0,25	0,09	0,53	0,09	0,31	0,08	0,68	-	0,69	-

Frequency (Hz)	**Case 02B: Ratio Between Speeds Measured** (with and without cross ventilation)									
	V2/V1		V3/V1		V4/V1		V5/V1		V6/V1	
	2B A	2B F	2B A	2B F	2B A	2B F	2B A	2B F	2B A	2B F
3	0,59	0,46	0,53	0,46	0,47	0,44	0,70	-	0,78	-
5	0,45	0,26	0,41	0,26	0,28	0,25	0,72	-	0,78	-
7	0,26	0,15	0,46	0,15	0,21	0,15	0,69	-	0,74	-
9	0,23	0,13	0,46	0,13	0,18	0,12	0,69	-	0,73	-
11	0,23	0,11	0,44	0,12	0,18	0,11	0,68	-	0,71	-
13	0,25	0,09	0,41	0,10	0,18	0,08	0,69	-	0,74	-

Informations:

1A A= Case 01A with cross ventilation;
1A F= Case 01A without cross ventilation;
1B A= Case 01A with cross ventilation;
1B F= Case 01B without cross ventilation;
2A A= Case 02A with cross ventilation;
2A F= Case 02A without cross ventilation;
2B A= Case 02B with cross ventilation;
2B F= Case 02B without cross ventilation.

4. Conclusions

The results of wind tunnel tests show a ventilated window-sill was the best façade configuration regarding natural ventilation. Such a solution was better than the ventilation modules positioned separately above and below the façade. Cross ventilation provides higher speed and a better internal distribution of air.

For cases with openings in only one façade (without cross ventilation), the ventilation is low, i.e., approximately the same, regardless of the type of solution. The average speed of the internal wind will probably not change significantly if the size of the inlet opening increases for cases without cross ventilation. The use of other types of devices in the façade (e.g. a vertical louver) may direct the air flow to the input and the internal speeds may slightly increase. However, cross ventilation would still be ideal for a better natural ventilation. Such results have proven the necessity of openings opposite or adjacent to the wall for better natural ventilation.

The choice for the natural ventilation solution also depends on a detailed analysis of climate conditions. Natural ventilation in buildings maintains the indoor air quality and provides thermal comfort through the air movement. As this study focused on a modular façade system for Portugal, such ventilation solutions can be used in the south of the country, during the summer season and no pre-heating of the inlet air is necessary.

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